Observing Gravitational Waves from Spinning Neutron Stars

Reinhard Prix (Albert-Einstein-Institut)

for the LIGO Scientific Collaboration

Orsay, 28 June 2006

Outline

1. Astrophysical Motivation
   - Gravitational Waves from Neutron Stars?
   - Emission Mechanisms (Mountains, Precession, Oscillations, Accretion)
   - Gravitational Wave Astronomy of NS
2. Detecting Gravitational Waves from NS
   - Status of LIGO (+GEO600)
   - Data-analysis of continous waves
   - Observational Results

Outline

Orders of Magnitude

Quadrupole formula (Einstein 1916).
GW luminosity (ϵ: deviation from axisymmetry):

$$L_{\mathrm{GW}} \sim \frac{G}{c^5}\,\epsilon^2\left(\frac{M\,V^3}{R}\right)^2$$

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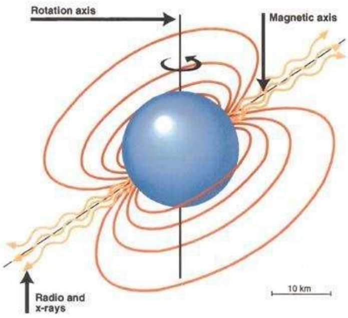
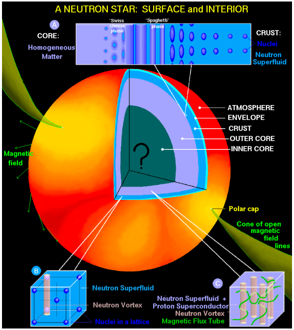
☞ Need compact objects in relativistic motion:
Black Holes, Neutron Stars, White Dwarfs

What is a neutron star?





Mass: $M \sim 1.4\, M_\odot$ Rotation: $\nu \lesssim 700\ s^{-1}$

Radius: $R \sim 10\ \mathrm{km}$ Magnetic field: $B \sim 10^{12} - 10^{14}\ \mathrm{G}$

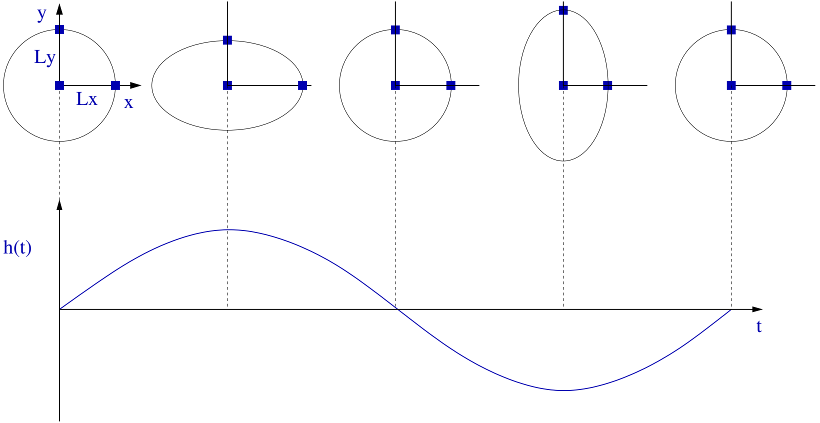
$\Longrightarrow$ density: $\bar{\rho} \gtrsim \rho_{\mathrm{nucl}}$

$\Longrightarrow$ relativistic: $\frac{R_s}{R} = \frac{2GM}{c^2 R} \sim 0.4$

Gravitational Wave Strain $h(t)$

Plane gravitational wave $h^{+}_{\mu\nu}$ along z-direction:

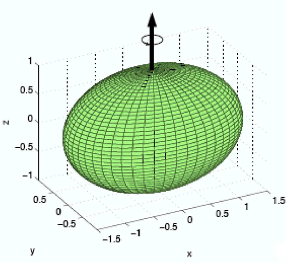
Strain $h(t) \equiv \frac{L_x - L_y}{2L}$:



Triaxial Spinning Neutron Stars

Rotating neutron star:

- non-axisymmetric $\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$
- rotation rate ν



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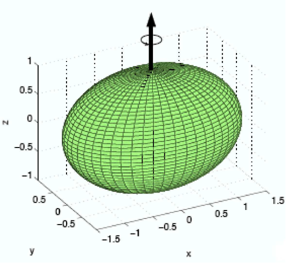
☞ GW with frequency $f = 2\,\nu$

Strain-amplitude h_0 on earth:

$$h_0 = \frac{16\pi^2\, G}{c^4}\, \frac{\epsilon\, I_{zz}\, \nu^2}{d}$$



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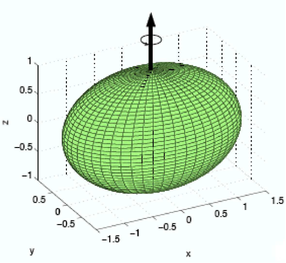

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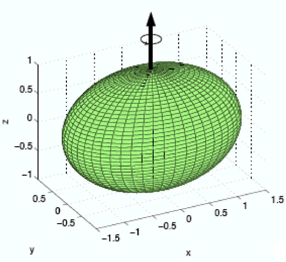

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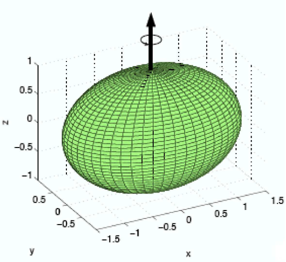

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☞ NS signals buried in the noise $\Longrightarrow$ need “matched filtering”

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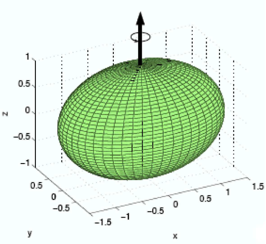
- “Mountains”
- Oscillations
- Free precession
- Accretion (driver)



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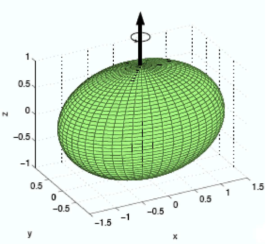

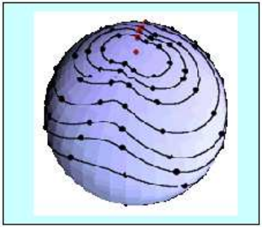

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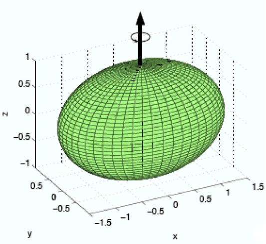

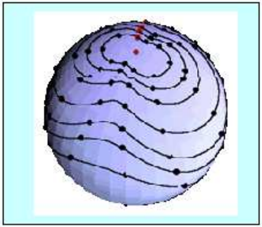

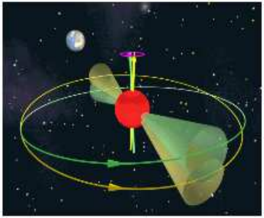

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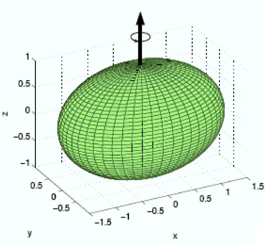

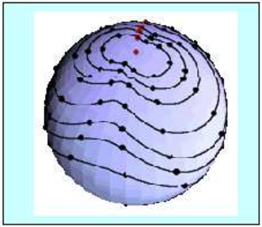

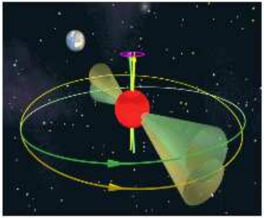

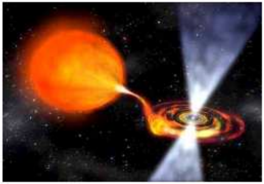

Neutron Star “Mountains”

- Conventional NS crustal shear mountains:
  - ☞ $\epsilon_{\rm crust} \lesssim 10^{-7} - 10^{-6}$ (Ushomirsky, Cutler, Bildsten)
- Superfluid vortices: Magnus-strain deforming crust
  - ☞ $\epsilon_{\rm Magnus} \sim 5 \times 10^{-7}$ (D.I. Jones; Ruderman)
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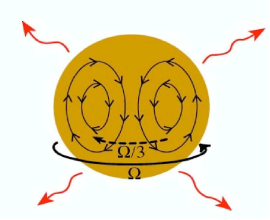
Oscillation Modes



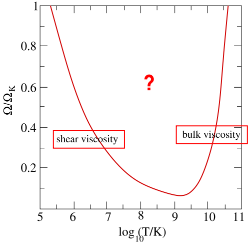
Chandrasekhar-Friedman-Schutz instability:

counter-rotating mode "dragged forward"
$\Longrightarrow$ negative energy and angular momentum

☞ emission of GW amplifies the mode

☞ counteracted by dissipation

r-mode instability window:

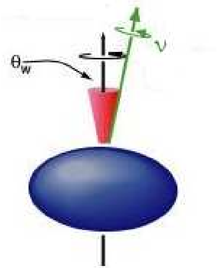


Open questions:

- Dissipation mechanisms: vortex friction, hyperons, crust-core coupling,...
- saturation amplitude, mode-mode coupling, evolution timescales

Free Precession

"Most general motion of a rigid body" (Landau&Lifshitz 1976)

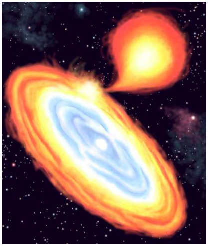


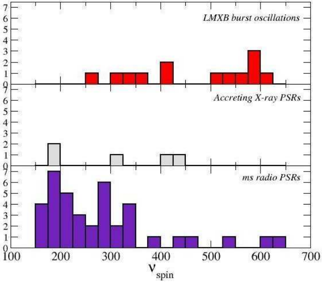
NS are not rigid: coupled crust - core (viscosity + superfluid vortex pinning)

- likely to be damped rapidly
- no obvious instability or "pumping mechanism"

$$h_0 \sim 10^{-26} \left(\frac{\theta_w}{0.1}\right) \left(\frac{100\,\mathrm{pc}}{d}\right) \left(\frac{\nu}{500\,\mathrm{Hz}}\right)^2$$

Accretion





Breakup-limit $\nu_K \sim 1.5$ kHz ☞ What limits the NS-spin?

Bildsten, Wagoner: Accretion-torque = GW torque ($\propto \nu^5$)

Observed X-ray flux ☞ Sco X-1: $h_0 \sim 3 \times 10^{-26}\,(270\,\mathrm{Hz}/\nu)^{1/2}$

Outline

Astrophysics Summary

- NS are plausible sources for LIGO I, II or VIRGO
- Whether or not they are detectable depends on many poorly-understood aspects of NS physics
- ☞ Any GW-detection from rotating NS will be extremely valuable for NS physics
- ☞ Even the absence of detection can yield astrophysically interesting information (crust deformation, B, instabilities)
- NS physics producing GWs is very different and complementary to electromagnetic emission (bulk-mass motion vs magnetosphere-electron motion)

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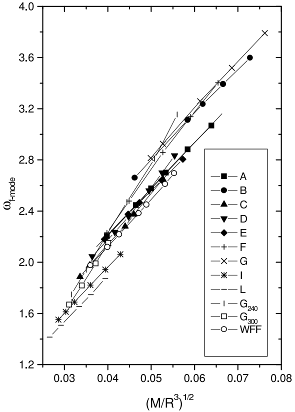
Gravitational Wave Astronomy

"Astero-Seismology" (Andersson, Kokkotas 1998): f-mode



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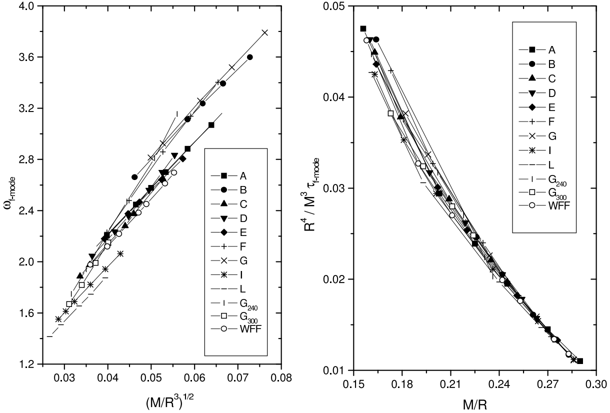

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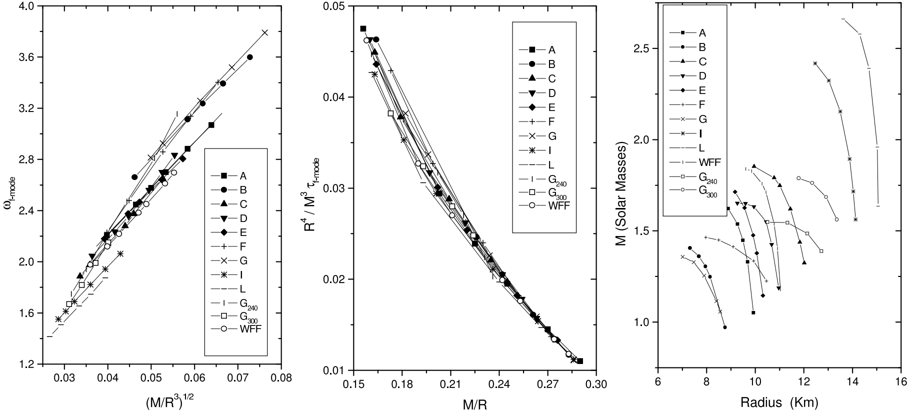

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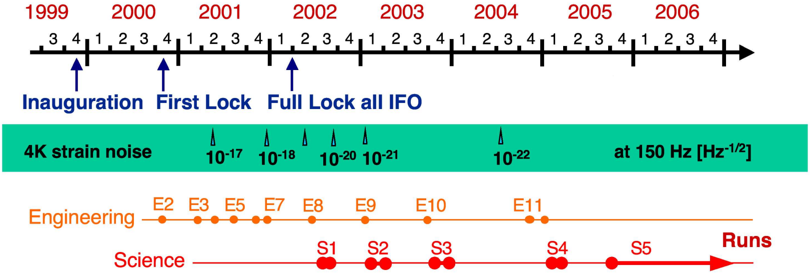
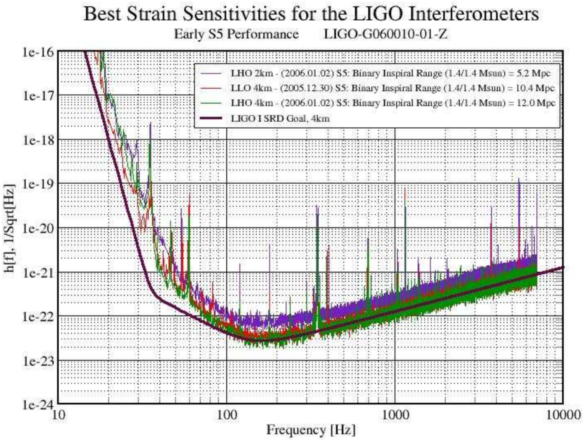
LSC detectors: LIGO + GEO600



Current LIGO noise performance



$$h_0 = \frac{\Delta L}{L} \sim 3 \times 10^{-23} \Longrightarrow \Delta L \sim 10^{-19}\ m = 10^{-4}\ fm!!$$

LSC Data Analysis

LIGO (H1, H2, L1) and GEO600 data analyzed within the LIGO Scientific Collaboration (LSC):
$\sim$ 40 institutions, $\sim$ 320 authors (S3)

4 major search groups (different targets and methods):

- Binary inspirals: short inspiral signals (*modeled*)
- Bursts: short *unmodeled* signals (supernovae, merger)
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Outline

1. Astrophysical Motivation
   - Gravitational Waves from Neutron Stars?
   - Emission Mechanisms (Mountains, Precession, Oscillations, Accretion)
   - Gravitational Wave Astronomy of NS
2. Detecting Gravitational Waves from NS
   - Status of LIGO (+GEO600)
   - Data-analysis of continous waves
   - Observational Results

Nature of GW from Rotating Neutron Stars

- NS frame: monochromatic wave, slowly varying frequency

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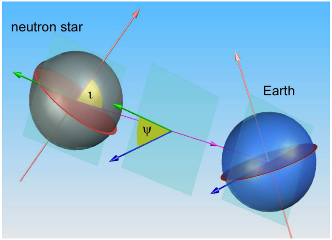

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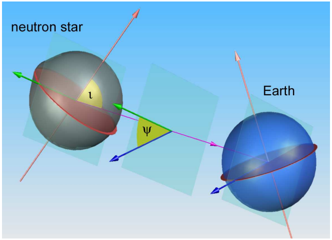

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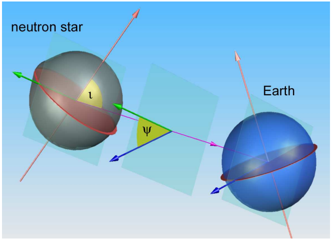

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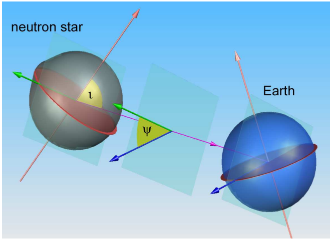

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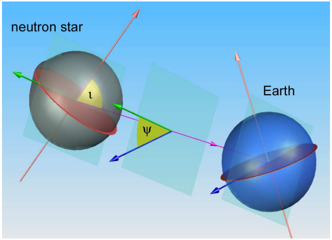

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multi-detector vector $\{\boldsymbol{x}(t)\}^{\mathrm{X}} = x^{\mathrm{X}}(t)$ with $\mathrm{X} \in \{\mathrm{H1}, \mathrm{L1}, \mathrm{V1}...\}$

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$$\mathrm{SNR} = \sqrt{(\boldsymbol{s}|\boldsymbol{s})} \propto \frac{h_0}{\sqrt{S_n}} \sqrt{T\,\mathcal{N}}$$

T ... observation time
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$h_0/\sqrt{S_n} \ll 1$ ☞ need long T (and many detectors $\mathcal{N}$)

Matched filtering IV: parameter-space covering

The *covering problem*

Choose a finite number N_p of “templates” $\lambda_{(k)}$, such that

1. never lose more than a fraction m at closest template $\lambda_{(k)}$
2. N_p is the smallest possible number satisfying 1

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$N_p \propto T^5$ ... but NO scaling with $\mathcal{N}$! (R. Prix, gr-qc/0606088)

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Relative loss in mismatched $\mathcal{F}(\lambda)$ at $\lambda = \lambda_{\rm sig} + \Delta\lambda$:

$$\mathcal{F}(\lambda) = \mathcal{F}(\lambda_{\rm sig})\left(1 - g_{ij}\,\Delta\lambda^i\Delta\lambda^j + ..\right) \implies \text{"metric" } g_{ij}$$

$$N_p \propto \int_{\{\lambda\}} \sqrt{\det g_{ij}}\; d^n\lambda$$

☞ isolated NS $\lambda^i = (\alpha, \delta, f, \dot{f})$:

$N_p \propto T^5$... but NO scaling with $\mathcal{N}$! (R. Prix, gr-qc/0606088)

Computing "cost": $C_p \propto \mathcal{N}\, T^6$

Cost-benefit example: LIGO + VIRGO

Assume similar sensitivity H1 $\sim$ L1 $\sim$ V1

$$N_p \propto T^5 \qquad C_p \propto \mathcal{N}\, T^6 \qquad \mathrm{SNR} \propto \sqrt{\mathcal{N}\, T}$$

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H1+L1	T_0	ρ_0	C_0
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V1	$2\,T_0$	ρ_0	$32\,C_0$
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Combining (similar-sensitivity) detectors is the computationally cheapest way to increase sensitivity!

(at fixed computing power $\Longrightarrow$ highest sensitivity)

Search Strategies

- Wide-parameter searches for unknown NS:

- Targeted searches for known pulsars ($f = 2\nu$)

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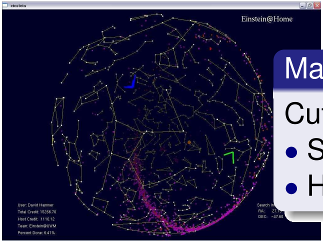
- Targeted searches for known pulsars ($f = 2\nu$)
  ☞ only *one* template $\lambda_0 = \{\alpha, \delta, f, \dot{f}, ..\}$ from radio/X-ray
  Fully coherent, not computationally limited ($T \sim$ data),
  $\Longrightarrow$ most sensitive search!

Einstein@Home: Search for Unknown NS



Maximize available computing power

Cut parameter-space λ in small pieces $\Delta\lambda$

- Send workunits $\Delta\lambda$ to participating hosts
- Hosts return finished work and request next

- Public distributed computing project, launched Feb. 2005
- Currently $\sim$120,000 active participants, $\sim$50Tflops
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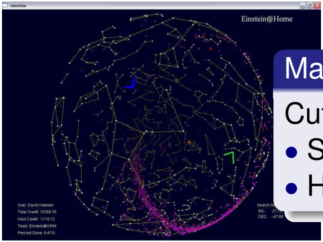

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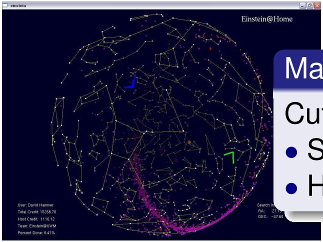

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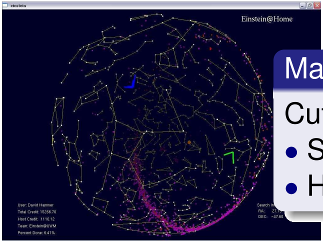

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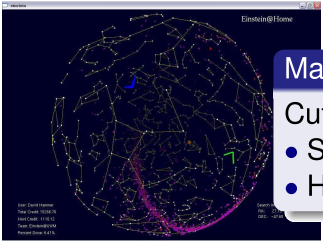

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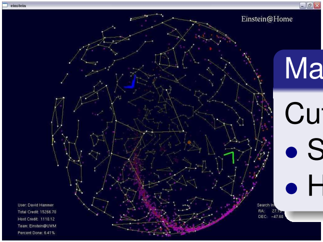

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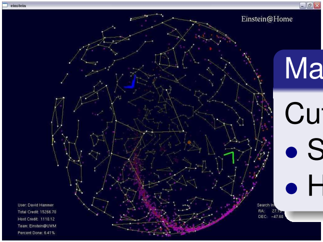

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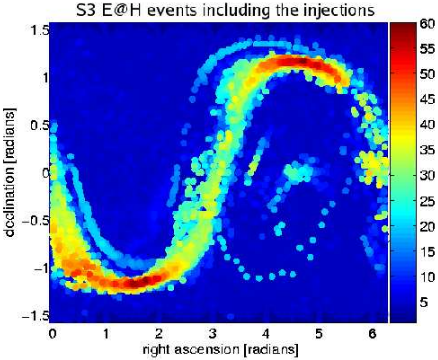
Outline

Einstein@Home S3 results



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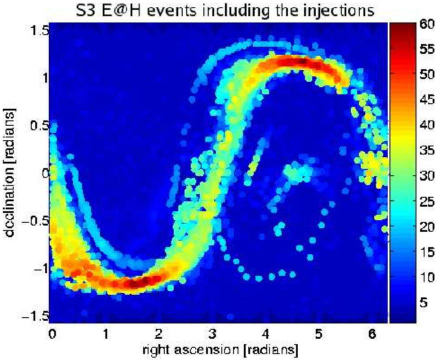

- correctly identified injections ($h_0 \sim 10^{-23}$)

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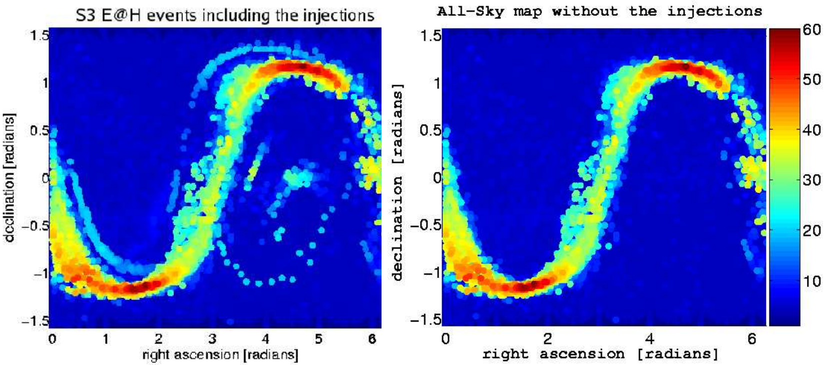

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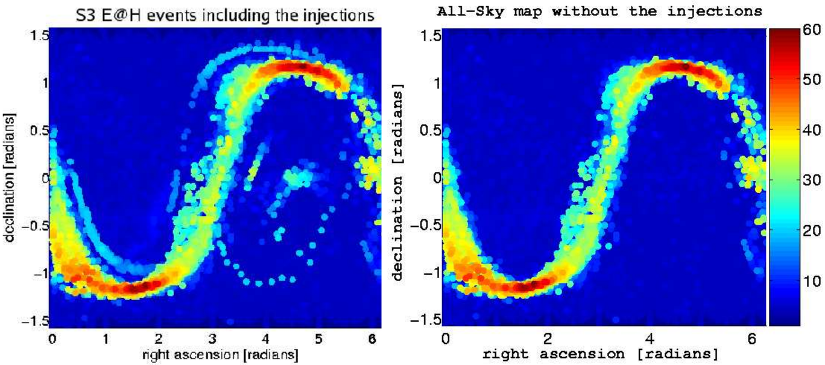

- correctly identified injections ($h_0 \sim 10^{-23}$)
- all "outliers" either on $\boldsymbol{r}(t) \cdot \boldsymbol{n} = 0$ circles (☞ stationary lines), or ruled out by follow-up studies (S4)

Wide-Parameter Searches: (Best) Upper Limits

- Fully coherent ($\mathcal{F}$-statistic) searches `[gr-qc/0605028]`:

- Semi-coherent searches:

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Early S5 PowerFlux: all-sky, isolated NS ($f \in [40, 700]\mathrm{Hz}$)
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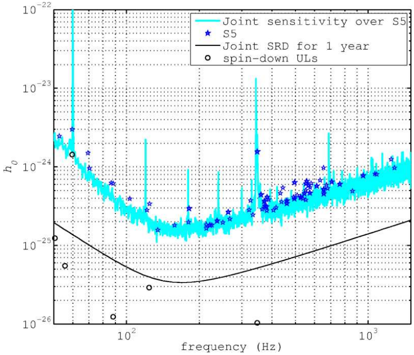
Targeted Pulsar Search: Early S5 (*preliminary*)



- Targeted 73 pulsars ($f = 2\nu$): 32 isolated, 41 binary (29 in GCs)
- first 2 months of S5
- all 3 detectors: H1, H2, L1
- Best 95% upper limits:
  $h_0 \lesssim 2 \times 10^{-25}$ (PSR J1603-7202)
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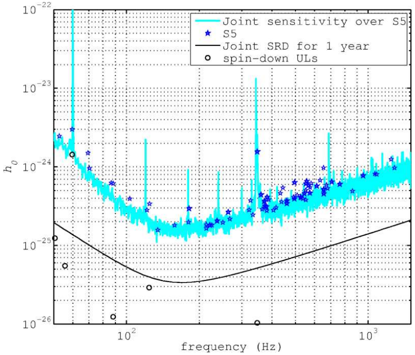

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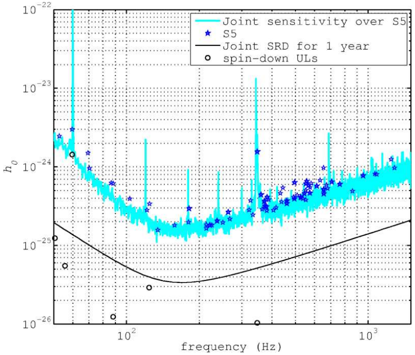

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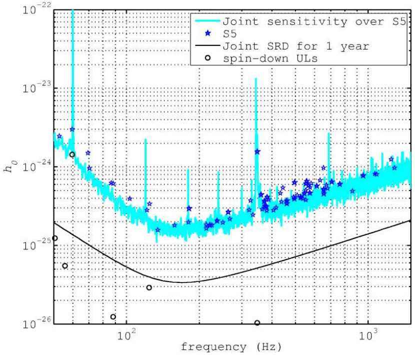

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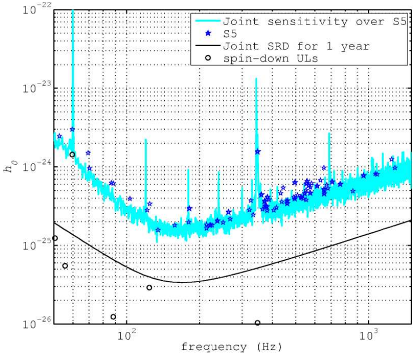

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Upper-limits well above *spindown-limit* (except in GCs)

But: Crab-pulsar is only a factor 2.1 away from spindown-limit

☞ will (most likely) be able to beat spindown-limit during S5!

Published results

Published LSC results of neutron-star searches:

- S1 Setting upper limits on the strength of periodic gravitational waves from PSR J1939 + 2134 using the first science data from the GEO 600 and LIGO detectors, B. Abbott et al. (LSC), Phys. Rev. D 69, 082004 (2004)
- S2 Limits on gravitational wave emission from selected pulsars using LIGO data, B. Abbott et al. (LSC), Phys. Rev. Lett. 94, 181103 (2005)
- S2 First all-sky upper limits from LIGO on the strength of periodic gravitational waves using the Hough transform, B. Abbott et al. (LSC), Phys. Rev. D 72, 102004 (2005)
- S2 Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: results from the second LIGO science run, to be submitted, `[gr-qc/0605028]`
- S3 Online report on Einstein@Home results for S3 search: `http://einstein.phys.uwm.edu/PartialS3Results/`

Summary and outlook

- No GW detection so far, but none expected
  ☞ setting upper limits on h_0 and ϵ
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- LIGO S5 operating at design-sensitivity, will collect one year's worth of data (duration ~1.5 years)
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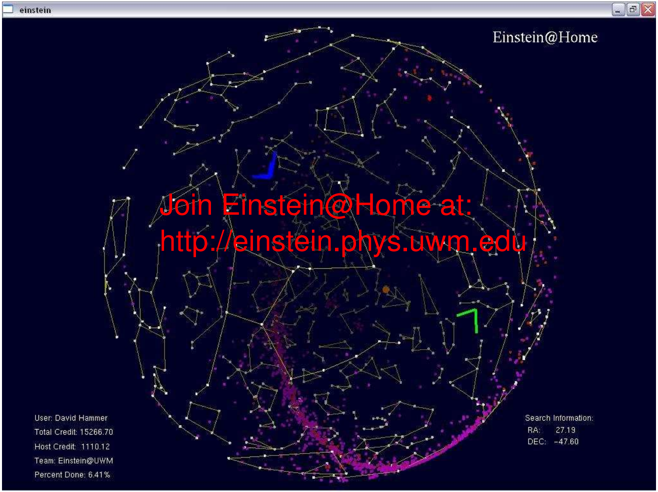
You can help us find Gravitational Waves!



The "spindown-limit" (for known pulsars)

Energy lost in GW: $\frac{dE_{\mathrm{GW}}}{dt} \propto \nu^6 \, I_{zz}^2 \, \epsilon^2$

Rotational energy: $\frac{dE_{\mathrm{rot}}}{dt} \propto I_{zz} \underbrace{\nu \, \dot{\nu}}_{\text{observed}}$

Spindown limit

$$\frac{dE_{\mathrm{GW}}}{dt} \leq \frac{dE_{\mathrm{rot}}}{dt} \quad \Longrightarrow \quad \text{upper limit on } \epsilon \text{ and } h_0$$

☞ limit on deformation ϵ and amplitude h_0:

$$\epsilon_{\mathrm{sd}}^2 \propto \frac{1}{I_{zz}} \frac{\dot{\nu}}{\nu^5} \quad , \qquad h_{\mathrm{sd}} \propto \frac{\sqrt{I_{zz}}}{d} \sqrt{\frac{\dot{\nu}}{\nu}}$$